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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1720

FRICITION AT HIGH SLIDING VELOCITIES
OF SURFACES LUBRICATED WITH SULFUR AS AN ADDITIVE

By Robert L. Johnson, Max A. Swikert
and Edmond E. Bisson

Lewis Flight Propulsion Laboratory
Cleveland, Ohio



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SUMMARY

Friction occurring at high sliding velocities of sulfur-type extreme-pressure lubricants was investigated. Experimental evidence is presented that indicates the existence of a limiting and critical condition of sliding velocity.

The experiments were performed with an apparatus incorporating means for measuring sliding friction that consists basically of an elastically restrained spherical rider sliding in a spiral path on a rotating disk. The disk specimens were lubricated with cetane (normal hexadecane) and with cetane containing free sulfur or benzyl disulfide. The effects of concentration of free sulfur on friction and surface damage were determined. The experiments were conducted over a range of sliding velocities between 50 and 8000 feet per minute with loads from 269 to 1543 grams (126,000 to 225,000 lb/sq in., initial Hertz surface stress). Supplemental studies of friction specimens were made using standard physical, chemical, and metallurgical equipment and techniques.

The theory is advanced that rate of chemical reaction between surfaces and additives is a limiting factor in lubrication by extreme-pressure additives of surfaces operating at high sliding velocities. In support of this theory, the experiments indicated lubrication failures at high sliding velocities for solutions of sulfur in cetane. Above the critical velocity, friction increased and mass surface welding occurred. Variations in load and in sulfur concentration had no appreciable effect on the sliding velocity at which the initial lubricant failure occurred.

Experiments with pure cetane on clean steel and on a solid ferrous-sulfide film indicate that cetane may fail as a boundary lubricant by oxidation and that it influences the chemical and physical processes in sliding, which determine the degree and severity of surface failure. The roles of the base lubricant and of the additives

could not be so isolated as to suggest the possible reaction product of sulfur additives with steel surfaces.

INTRODUCTION

In the past, research data relative to extreme-pressure lubricant additives have been obtained either with experimental apparatus incorporating very low sliding velocities or with actual gear assemblies by which determination of true surface conditions is difficult (because of imperfect tooth profile, misalignment, and other errors). It is particularly difficult to determine surface contact pressures under such conditions. These facts impose definite limitations and restrictions on the research results and indicate a need for data obtained under a wider range of conditions such as an extension to high sliding velocities. The fundamental limitations of the lubrication by extreme-pressure additives must also be determined.

Pruett and co-workers (reference 1) and Beeck and co-workers (reference 2) have suggested theories of lubrication by additive agents that involve either chemical reaction or chemical "polishing." It is stated in reference 1 that: "... the function of 'extreme-pressure' additives in hypoid lubricants [is to] form films of low shear strength capable of withstanding temperatures produced by very high tooth pressures." These films are formed by chemical reaction. On the other hand, it is shown in reference 2 that, in the case of wear-reduction agents, the mechanism involves the alloying of the additive agent with the metal surface to form low-melting-point eutectics to produce chemical polishing. In the use of additive agents of the chemical-reaction type, the primary consideration has been that of minimizing corrosive tendencies while obtaining adequate lubrication rather than that of obtaining optimum lubrication. Chemical reaction must also be studied under certain conditions, such as at high sliding velocities.

Analytical considerations suggested the theory that limiting conditions of sliding may be reached, under conditions of high sliding velocities, when the rate of sliding exceeds that rate at which effective chemical reaction between additive and sliding surfaces can proceed, which causes failure of the lubricant. A friction study of the sliding rates in conjunction with additive action is necessary to determine the limitations. An investigation was therefore conducted at the NACA Cleveland laboratory to determine whether sliding velocity is a limiting factor in lubrication requiring extreme-pressure additives.

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The kinetic-friction characteristics of steel specimens lubricated with cetane (normal hexadecane) and with cetane containing free sulfur or benzyl disulfide as extreme-pressure additives were experimentally determined. The effects of concentration of free sulfur on friction and surface damage were also determined. Correlation data were obtained with cetane on a specially prepared solid film of ferrous sulfide. The investigation was made with loads from 269 to 1543 grams (126,000 to 225,000 lb/sq in., initial Hertz surface stress) at sliding velocities up to approximately 8000 feet per minute. Friction measurements were made by means of an apparatus that basically consists of an elastically restrained spherical rider sliding in a spiral path on a rotating disk. The spiral path followed by the rider was made to insure that the rider was at all times contacting virgin surfaces of the disk. This research is an extension of that reported in references 3 and 4, which present basic information necessary to the analysis of the research reported herein.

APPARATUS AND PROCEDURE

The experimental friction and wear studies were conducted with essentially the same equipment that is described in reference 3, but driven by a hydraulic motor. A diagrammatic sketch of the basic parts of the apparatus is presented in figure 1. The principal elements of the apparatus are the specimens, which are an elastically restrained spherical rider and a rotating disk. The rider is loaded by weights applied along the vertical axis of the rider holder. Friction force between the rider and the disk is measured by four strain gages mounted on a copper-beryllium dynamometer ring. The force is indicated by either a recording- or an indicating-type calibrated potentiometer. The coefficient of friction μ_k is computed from the equation

$$\mu_k = \frac{F}{P}$$

where F is the measured friction force and P is the applied normal load.

A motor-driven radial-feed mechanism, calibrated to indicate radial position of the rider, causes the rider to traverse a spiral path on the rotating disk so that no overlapping of the wear tracks occurs. The disk is mounted on a flywheel that is supported and located by bearings. The rotating specimen is driven through a

flexible coupling by a hydraulic motor operating under constant pressure with speed adjusted by varying the flow of hydraulic fluid; this arrangement allows good speed control over a range of sliding velocities between 50 and 18,000 feet per minute. The disk and rider are covered, permitting the operating atmosphere of dried air to be slightly pressurized.

The system for drying the air for the operating atmosphere consists, in series, of a filter tube 48 inches long containing surgical cotton, six silica-gel drying tubes, and an 8-inch tube containing activated alumina. The air is supplied by the laboratory compressed-air system.

In conducting the experiments, the disk is rotated at a predetermined speed and, by means of a cam arrangement, the loaded rider is lowered onto the disk as the radial feed is started. As the rider traverses the disk, friction force is observed or recorded with a potentiometer and disk rotative speed is determined with an electric revolution counter and a synchronized timer. The run is terminated by lifting the rider from the disk surface. Mean sliding velocity for the experiment was computed from the recorded rotative disk speed and the mean diameter of the rider path. The change in diameter of the rider path on the disk resulting from the radial travel of the rider caused a maximum deviation in sliding velocity of approximately 3 percent from the mean value. An unworn area of a rider was used in each run. In addition to the friction runs, special wear runs were made for each set of specimens at 2000 feet per minute for 6 seconds.

As reported in reference 3, uncontrolled variables, such as wear of the rider, natural frequency of the restraining assembly, and vibrations induced by the driving mechanism, had no appreciable effect on the accuracy of the data.

The physical and physicochemical conditions of the surface and the subsurface material of the research specimens were studied before and after the sliding-friction experiments by means of surface-roughness and surface-hardness measurements as well as electron-diffraction and metallographic techniques. During the experiments, no measurable change in surface hardness occurred. Because of the mass surface welding obtained and consequent extreme surface roughness, surface-finish measurements were not significant.

The friction data presented are complete data from a representative experiment for each lubricant-additive combination, selected from a mass of data from several experiments on each variable. For comparison purposes, a load of 269 grams is used for the majority of the

curves presented because this load produces an initial surface stress (126,000 lb/sq in., Hertz) that is in the range of limiting values used in design of components such as aircraft-engine propeller-reduction gearing.

SPECIMEN PREPARATION

As pointed out in references 3 and 4, careful preparation of specimens was found to be the most important single requisite for success of the experiments. The disk specimens were finished and cleaned according to the detailed procedure given in reference 3. The disk surfaces were so finished as to minimize surface working and to give a uniform, nondirectional surface finish with a roughness of 3 to 6 microinches rms as measured with a Profilometer. The 13-inch-outside-diameter disk specimens were of normalized SAE 1020 steel, Rockwell number A-50. The rider specimens used were commercial balls, 1/4 inch in diameter, of SAE 1095 steel hardened to Rockwell number C-60. They were not subjected to laboratory finishing operations before use but were cleaned and rinsed in 190-proof ethyl alcohol.

In order to evaluate properly the effect of the extreme-pressure additives in these experiments, it was necessary to select a base lubricant that would introduce a minimum of experimental variables. Cetane $\text{CH}_3(\text{CH}_2)_{14}\text{CH}_3$ was selected because it is liquid at the temperature of the experiment and is readily available in a pure state (minimum purity, 95 percent). The cetane was stored in a dark room to prevent the promotion of its oxidation by light and was percolated through fuller's earth, alumina, and silica gel immediately prior to its use in any experiment in order to remove any polar compounds. Unreported preliminary results obtained with cetane not handled with such care were in poor agreement and served to indicate the necessity for these precautions to prevent contamination. The measured index of refraction for the percolated cetane used in these experiments (n_D^{20}) was 1.4347, which is the exact value given for pure cetane in reference 5 and indicates the high purity of the material used. The lubricants and additives were freshly mixed for each experiment and were heated to approximately 110° F to accelerate formation of the solutions. The mixtures were allowed to cool to room temperature before use.

The lubricants were handled at all times in glassware cleaned in a cleaning solution and were deposited on the disk specimen by drops from a clean platinum dipper. After the lubricant had spread over the whole surface, the disk was rotated at the maximum speed of the experiment (approximately 2500 rpm) for 5 minutes causing the

excess lubricant to be thrown off leaving only a very thin film. All experiments for one disk were completed within an hour of deposition of the film in order to eliminate evaporation of the film as a variable. Preliminary experiments indicated that reproducibility of a run could be obtained within the 1-hour period.

RESULTS AND DISCUSSION

Effect of Sliding Velocity for Initial Hertz Stress

of 126,000 Pounds Per Square Inch

Comparative experiments with sulfur additives as the primary variable were completed using a load that produced an initial Hertz surface stress of 126,000 pounds per square inch. Surface stresses approaching this value are of primary interest in design of gear-reduction units because this stress approximates the maximum design values commonly used. The results obtained in this manner within practical ranges of sliding velocities should be applicable to many current design problems. Subsequent discussion extends the ranges of operating variables beyond present usage to provide basic information that may be used in future designs for more extreme conditions of load and sliding velocity.

Effect of base lubricant. - The effect of sliding velocity on friction of specimens lubricated by pure cetane is shown in figure 2. In comparing these data with the curve for dry-steel specimens (reference 3), it is of interest to note the extremely high coefficient of friction value (slightly over 1.0) observed after the initial failure of the lubricant film. The initial lubrication failure is indicated by the extreme increase in slope of the friction curve that occurred at a sliding velocity of approximately 1500 feet per minute. It is possible that the lubricant failure was caused by oxidation of the cetane, its desorption from the slider surfaces, or its breakdown into components of lesser lubricating properties. Friction values of such magnitude for lubricated steel on steel as indicated after initial failure of the lubricant are unusual and it is considered probable that the lubricant showed such a great effect on friction by its possible prevention of the formation of effective surface oxides. The roles of surface oxides on sliders have been studied and discussed by many investigators, as summarized in reference 4; in particular the results presented in reference 6 indicate that, for readily oxidized materials, the lack of an effective oxide film could cause friction increases of the magnitude shown in figure 2 for the cetane-lubricated steel surfaces.

Effect of concentration of free sulfur. - The investigation of the effects of concentration of sulfur in the base lubricant was limited by the sulfur solubility. The maximum amount of free sulfur that could be dissolved in cetane at room temperature was $1\frac{1}{2}$ percent by weight. Crystals of sulfur were observed on the friction specimens during the course of the experiment with $1\frac{1}{2}$ percent of sulfur. These crystals were also observed, in lesser quantity, with solutions having $1\frac{1}{4}$ percent of sulfur but were not observed with any of the other concentrations.

The data of figure 3 show the effect of sliding velocity on friction for steel surfaces lubricated with cetane containing free sulfur at an initial Hertz stress of 126,000 pounds per square inch. Figure 3(a) shows the effect of 0.5-percent free sulfur in cetane and indicates a lubrication failure somewhat similar to that for the pure cetane (also shown for comparison in fig. 3(a)) in approximately the same speed range (1000 ft/min as compared to 1500 ft/min for cetane). The curve also indicates that the coefficient of friction is generally independent of sliding velocity in the range from 3000 to 7000 feet per minute. The points that define the curve for cetane plus 0.5-percent free sulfur are all the data from five experiments and are included to show the experimental error. The experimental error in coefficient of friction is within ± 0.02 except in isolated cases and this error represents the maximum limit for all the experiments.

The effect of concentration of dissolved free sulfur in cetane on friction at high sliding velocities is shown in figure 3(b). These results indicate that in all cases increased concentration reduced friction and that the effect was more pronounced in the medium range of sliding velocities (3000 to 4000 ft/min) after the lubrication had already undergone an initial breakdown. The initial breakdown of the lubrication is considered to have occurred in the range of sliding velocities at approximately 1000 feet per minute for all the concentrations, although the degree of failure varied considerably. Because initial lubrication failures for the various concentrations of sulfur all occurred within a comparatively small range of sliding velocities, the limiting conditions of sliding rates may have been reached at which the rate of sliding exceeds the rate at which an effective chemical reaction can occur. The low values obtained with concentrations of $1\frac{1}{4}$ and $1\frac{1}{2}$ percent sulfur may have been the result of the free crystals of sulfur on the disk surfaces. Evaluation of the role of such crystals in the friction results is not considered important because such precipitation would be undesirable and could not be tolerated in practical applications.

In order to show more graphically that lubrication failure occurred in the range of sliding velocities at approximately 1000 feet per minute, a series of photomicrographs were obtained for wear areas on rider specimens after runs at varied sliding velocities on a disk lubricated with cetane containing 0.5-percent sulfur. These photomicrographs, presented in figure 4, show that normal abrasive wear occurred at sliding velocities of 1000 feet per minute or less with no indication of surface welding (figs. 4(a) to 4(c)). At 1500 feet per minute (fig. 4(d)), the rider surface shows evidence of appreciable amounts of material transfer by surface welding; although the individual welds may be of small magnitude, this appearance is considered indicative of lubrication failure. In all cases at the higher sliding velocities, mass surface welding of the type shown in figures 4(e) and 4(f) occurred. The material transferred was sufficient to establish new wear areas; this appearance indicates complete lubrication failure. No quantitative comparison of wear-area diameters can be made in figure 4 because the sliding distance was not the same in all cases.

A series of photomicrographs of representative wear areas of rider specimens after 6 seconds sliding with a load of 269 grams (126,000 lb/sq in., initial Hertz stress) at 2000 feet per minute sliding velocity on disk surfaces lubricated with several concentrations of sulfur in cetane are presented in figure 5. For reference purposes, representative disk surfaces are also shown in figure 5. No distinct difference exists between the wear tracks on the disk surfaces lubricated with the various solutions; consequently, only two representative photomicrographs are presented. In all cases, including the 1.50-percent sulfur concentration, the indications of mass surface welding show that the lubrication had failed under these conditions. This indication holds for the high sulfur concentrations in spite of the low friction coefficients obtained with these concentrations.

It can be seen from figures 3 to 5 that at 2000 feet per minute all the lubricants had experienced their initial failures as determined by upward friction trends, abnormal surface disturbances, or both. The rider photomicrographs of figure 5 show that there have been large material transfers to the riders during the experiments, which is further evidence of the failure of the lubricant. Material transfers of such magnitude must be considered distinct from the minute transfer of material, which probably occurs in all boundary lubrication (references 7 and 8). In figures 4 and 5, the material transferred to the rider was of sufficient magnitude that completely new wear areas were established on the welded transferred material. The transferred material must have been strongly welded to the rider to enable the welded material to support the large unit loads and the transverse stresses that occurred during sliding.

The type of surface damage as seen in figure 5, was not noticeably influenced by the additive concentration, although the wear surface was much better defined on the specimens used in the experiments with cetane containing no additive. In all the experiments, it is quite obvious that at the conditions of sliding for the specimens in figure 5 the wear process consisted largely in establishing and breaking large welds, thus tearing material from the sliders, rather than abrading or plowing as is characteristic of effective boundary lubrication (figs. 4(a), 4(b), and 4(c) and also fig. 9(b) of reference 3).

Effect of cetane on solid ferrous sulfide film. - In an attempt to determine whether ferrous sulfide was the primary reaction product formed on steel surfaces lubricated with sulfur additive lubricants, experiments were conducted with disk surfaces pretreated, as described in reference 4, to have solid films of ferrous sulfide and these disks were then lubricated with pure cetane. It was thought that some correlation of the friction results might be obtained that would indicate whether effective ferrous sulfide was formed on the sliders in the presence of sulfur additive lubricants at sliding velocities higher than that at which the initial lubricant failure occurred.

The data obtained with cetane on ferrous sulfide as well as reference data for pure cetane, cetane plus 0.5-percent sulfur, and dry solid ferrous sulfide (from reference 4) are presented in figure 6. If the relative effects of the base lubricant element and of the additive element could be separated and if these effects are nonadditive, the measured friction value when both are present would be expected to be that for the element giving the lower friction. In other words, the element which causes the minimum friction would be predominant. This explanation of the results of figure 6 holds for sliding velocities above 2000 feet per minute in this experiment; however, for the lower velocities it does not hold for some unknown reason. Above 2000 feet per minute, the data reproduce very closely those obtained for dry-ferrous-sulfide films, which were reported in reference 4. These data indicate that, at those conditions, the cetane had no effect on friction and it is considered probable that the heat energy released at the higher sliding velocities was sufficient to cause oxidation of the cetane or its desorption from the slider surface.

It is interesting to note that in figure 6 the curve for pure cetane on clean steel intersects the curve for dry ferrous sulfide near the point at which the curve for cetane-lubricated ferrous

sulfide becomes asymptotic with that for dry ferrous sulfide. This occurrence may further indicate that oxidation or desorption of the effective lubricating film of cetane occurred at a sliding velocity of approximately 2000 feet per minute.

The minimum-friction points for the cetane-lubricated ferrous sulfide occurred at the lowest sliding velocities and corresponded very closely with those points obtained with the additive lubricant on clean steel. The disparities between these curves at sliding velocities from 500 to 3000 feet per minute may indicate an effect of some unknown variable. These inequalities may be partly explained, however, if the failure of the lubrication by cetane is considered to be caused by oxidation rather than desorption. Sulfur compounds are commonly used as oxidation inhibitors in petroleum products. If the sulfur additive in these experiments acts as an oxidation inhibitor and the failure of cetane is caused by oxidation, the disparities between the curves for pure cetane on a ferrous-sulfide film and that obtained with cetane containing a sulfur additive on clean steel can be resolved. In this manner, the sulfur would retard the oxidation of the cetane and thereby delay the lubrication failure until a higher sliding velocity was reached.

Wear areas on the rider and disk specimens after 6 seconds of operation with a load of 269 grams at a sliding velocity of 2000 feet per minute with the disk surface consisting of prepared ferrous sulfide lubricated with pure cetane are shown in figure 7. The type of surface disturbance is generally comparable with that observed for dry ferrous sulfide in reference 4, although the wear is more of the abrading type when cetane is present; the presence of the cetane, however, caused a reduction in wear (wear-spot diameter, 0.030 in. as compared to 0.043 in. from reference 4). There is no indication of severe surface welding in these photomicrographs, although the wear was greater than that experienced in most experiments with cetane as the lubricant. The trailing edge of the wear spot on the rider (left edge of fig. 7(a)) shows an accumulation of extraneous material that is believed to be ferrous sulfide from the disk.

Effect of benzyl disulfide as additive. - Free sulfur was selected as the additive in the experiments reported because it was readily available in a pure form, and consequently the effectiveness of the additive would be limited to the effect of the sulfur alone. Organic sulfur compounds such as benzyl disulfide are more commonly used in extreme-pressure lubricants than free sulfur. Examples of the use of both benzyl disulfide and free sulfur as lubricant additives are contained in references 1 and 9. In order to check the effectiveness

of free sulfur as compared with other types of sulfur additive in compounded lubricants, experiments were made to determine the relative effects on sliding friction of equal concentrations of sulfur obtained from either benzyl disulfide or free sulfur. The results of these experiments are shown in figure 8. These friction results agree closely at sliding velocities below 2000 feet per minute and also there was essentially no difference in the initial points of lubricant failure. At the higher sliding velocities, the data agreement is not within the range of normal reproducibility. This disagreement may be ascribed to unknown constituents in the commercial additive used. It is interesting to note that the curve for 0.75-percent free sulfur (fig. 3(b)) checks the curve for 0.5-percent sulfur using benzyl disulfide (fig. 8) very closely at the higher sliding velocities.

Effect of Sliding Velocity for Variable Loads

In order to establish further the effect of rate of chemical reaction on lubrication by sulfur additive lubricants, it was considered important to determine the effects on the point of lubricant failure (as determined by friction trend) of the heat generated by a variable other than sliding velocity. Increased loading is a convenient manner of increasing the quantities of work energy dissipated as heat in friction without changing other important variables. It has been indicated by Bowden and Ridler (reference 10) that with sliding velocities of the magnitude being considered, at all except very light loads, the local surface temperatures are probably independent of load. Fundamentally therefore, if temperature is the factor of primary importance in the rate of chemical reaction by the additive, load should have little effect. The larger amounts of work energy released at higher loads would probably be reflected in higher mass temperatures. Such considerations introduce, as a factor possibly of prime importance, the mechanical activation of chemical reactions as described by Shaw in reference 11.

Experiments were conducted with specimens lubricated by cetane containing 0.5-percent dissolved free sulfur inasmuch as that concentration is in the intermediate solubility range and is used in commercial oils. The results of these experiments, presented in figure 9, show that the initial lubrication failure occurred at very nearly the same sliding velocity for a number of loads, although a small effect of load is apparent. These data indicate that the point of initial lubricant failure is very nearly independent of load and therefore that the quantity of heat energy released is insufficient to affect appreciably the rate of chemical reaction. It is interesting to observe that at a sliding velocity of 3000 feet per minute friction is substantially independent of load. In general, other sulfur concentrations showed the same effect of load on friction.

The friction curves for both dry and lubricated steels are also presented in figure 9 for comparison with the variable-load curves. Both of these curves are for loads of 269 to 1017 grams (126,000 to 194,000 lb/sq in., initial Hertz stress). The variable-load curves for 0.5-percent sulfur in cetane indicate that, at speeds above the initial point of failure, the agreement of coefficient of friction values with those for dry steel is good.

SUMMARY OF RESULTS

An experimental investigation has been conducted with a kinetic-friction apparatus consisting basically of an elastically restrained spherical rider sliding on disks lubricated with cetane (normal hexadecane) containing several concentrations of free sulfur in solution. The experiments were conducted over a range of velocities between 50 and 8000 feet per minute with loads from 269 to 1543 grams (12,000 to 225,000 lb/sq in., initial Hertz surface stress), and with supplemental studies using standard physical, chemical, and metallurgical equipment and techniques. The following results have been observed:

1. In support of the theory that rate of chemical reaction is a limiting factor in lubrication by extreme-pressure additives of surfaces operating at high sliding velocities, the experiments indicated definite lubrication failures at high sliding velocities. This theory is not limited to the conditions of these experiments but may also be of importance with other additives within ranges of sliding velocities that are of practical importance.
2. Free sulfur in cetane was an ineffective extreme-pressure lubricant for use at sliding velocities above approximately 1000 feet per minute. Above that velocity, complete failure of lubrication occurred with accompanying increase in friction, mass surface welding, or both.
3. Variations in load and in sulfur concentrations had no appreciable effect on the sliding velocity at which lubricant failure occurred. These factors influenced the friction values but did not change the point of failure. Friction decreased somewhat with increased sulfur concentration and in the region of the initial sliding velocity (1000 ft/min) friction increased with greater loads.
4. It was impossible to separate completely the relative effects of the base lubricant and the solid ferrous-sulfide film, but it was shown that the cetane lubrication failed at sliding velocities

greater than approximately 2000 feet per minute. This failure may have been caused by oxidation of the cetane under the conditions of high energy dissipation.

5. Friction values obtained with pure cetane on steel were unusually high at high sliding velocities. The cetane film was believed to have shown such a great effect on friction by its possible prevention of the formation of surface oxides.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, July 26, 1948.

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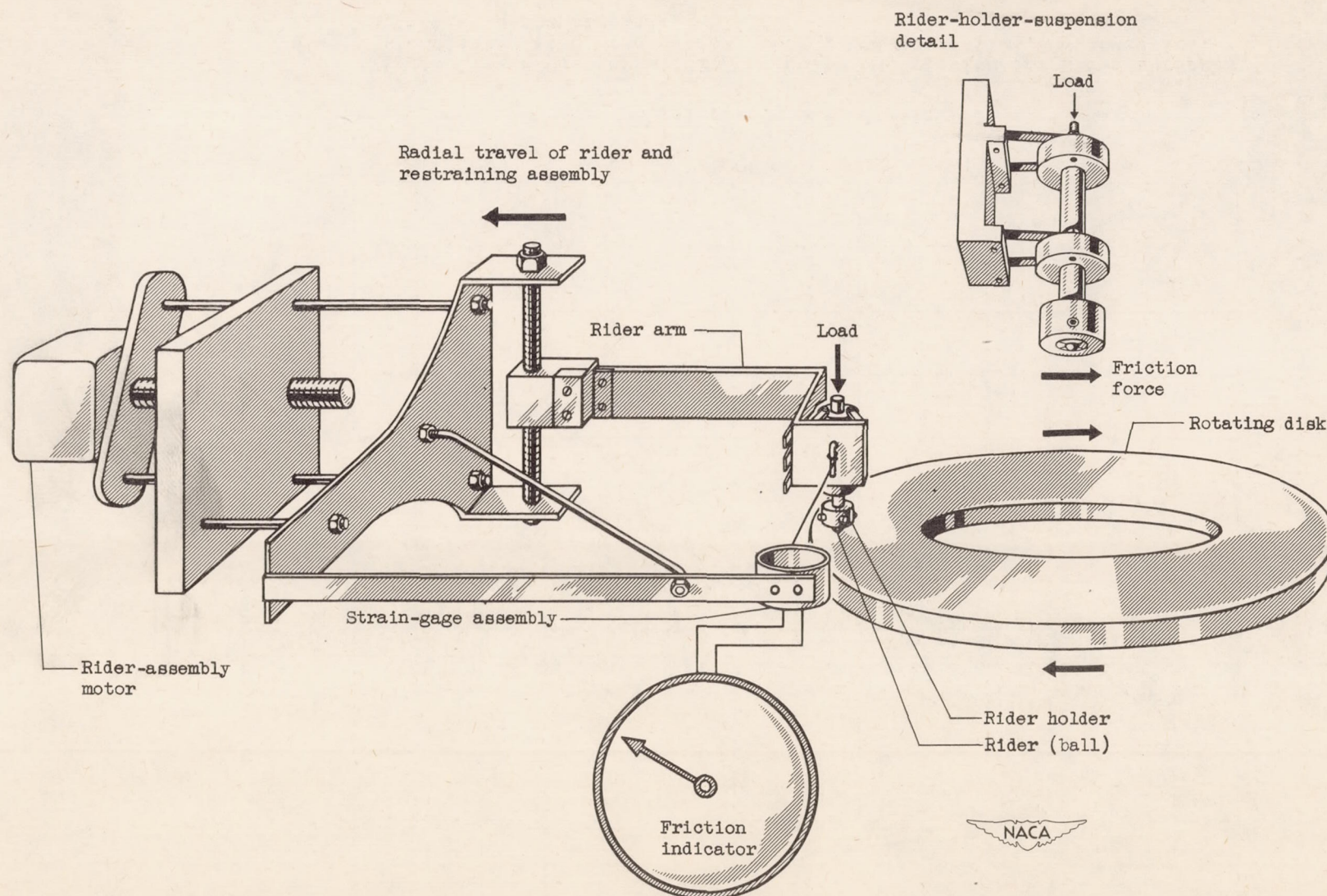


Figure 1. - Schematic diagram of sliding-friction apparatus.

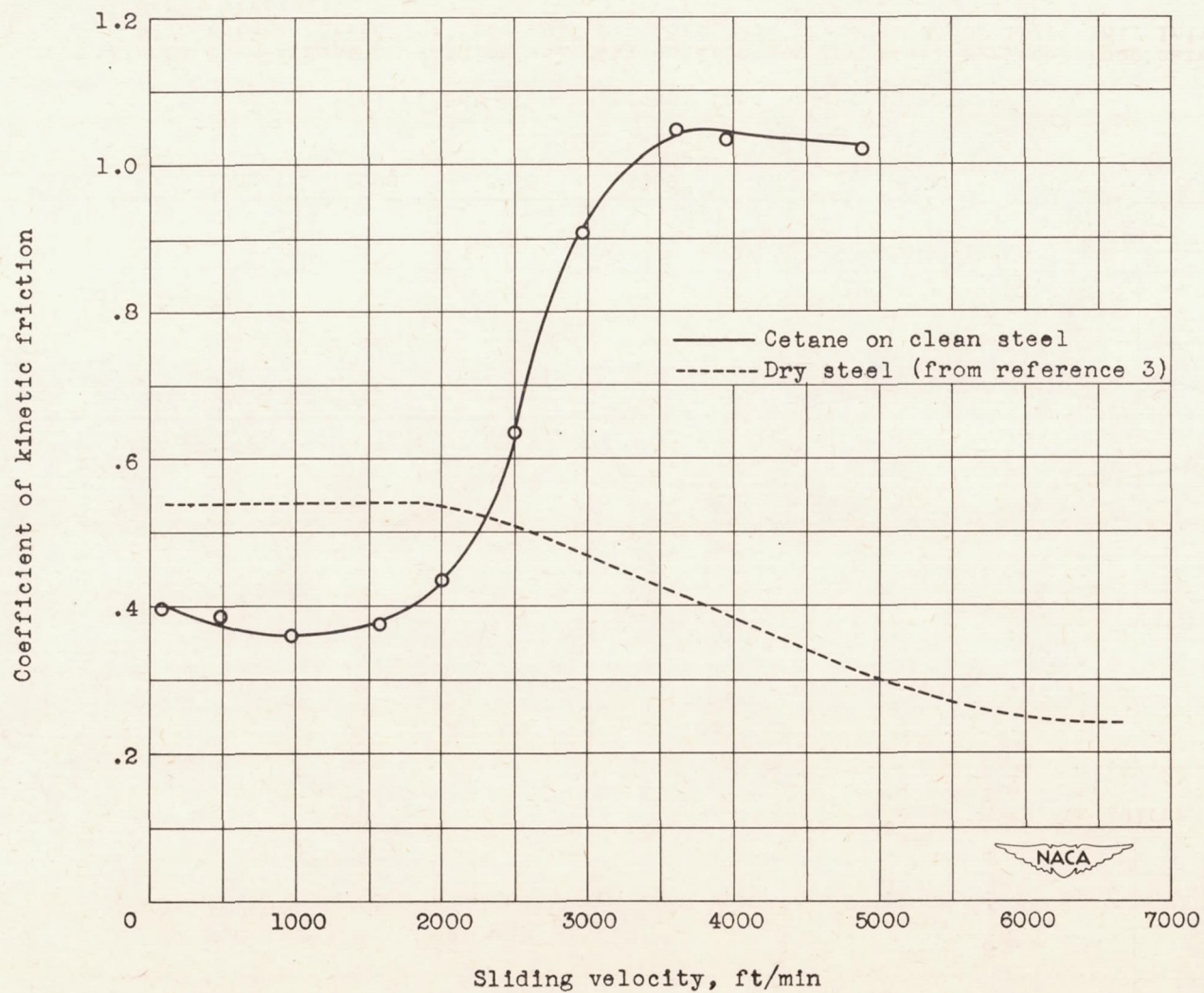
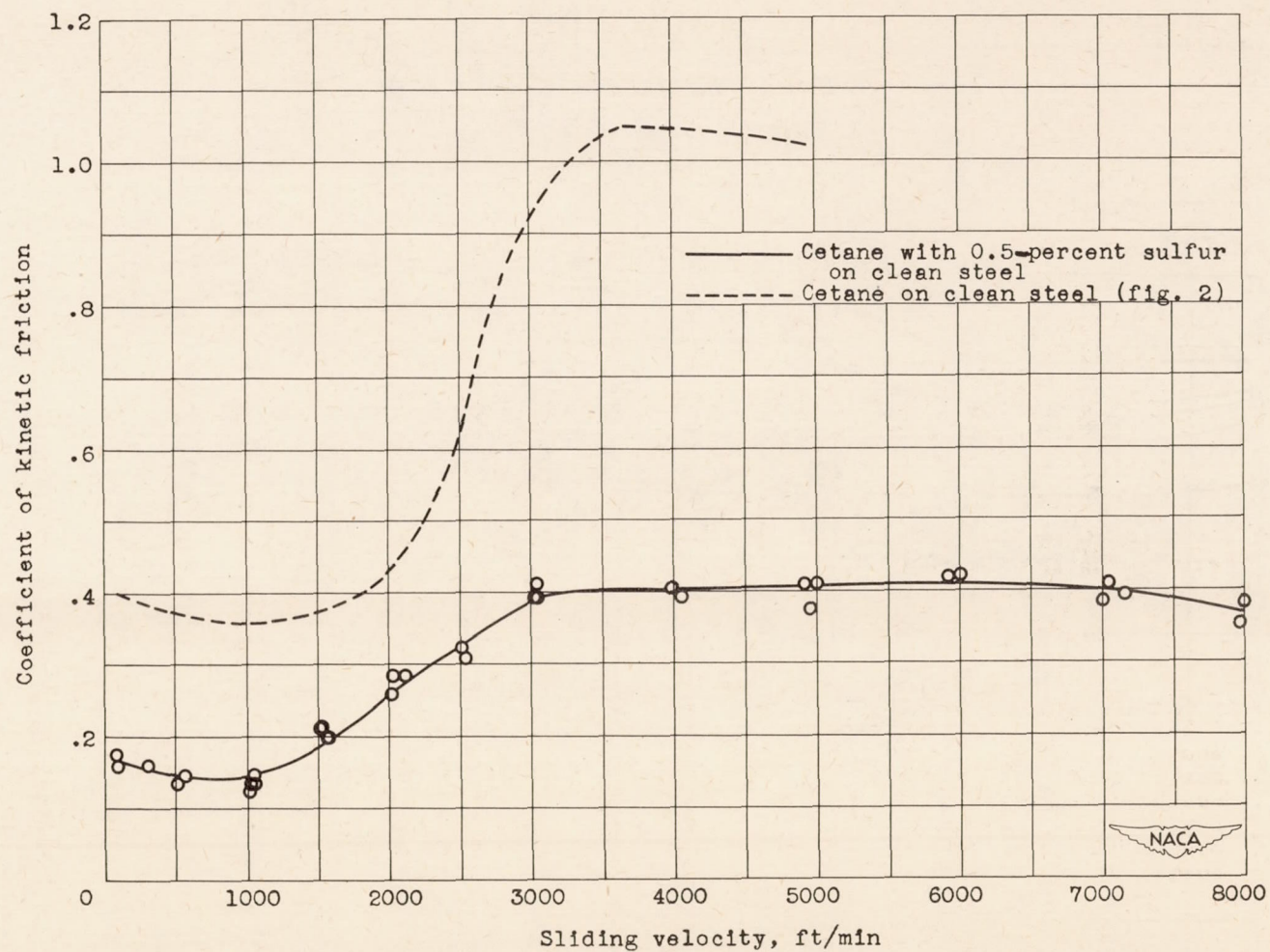
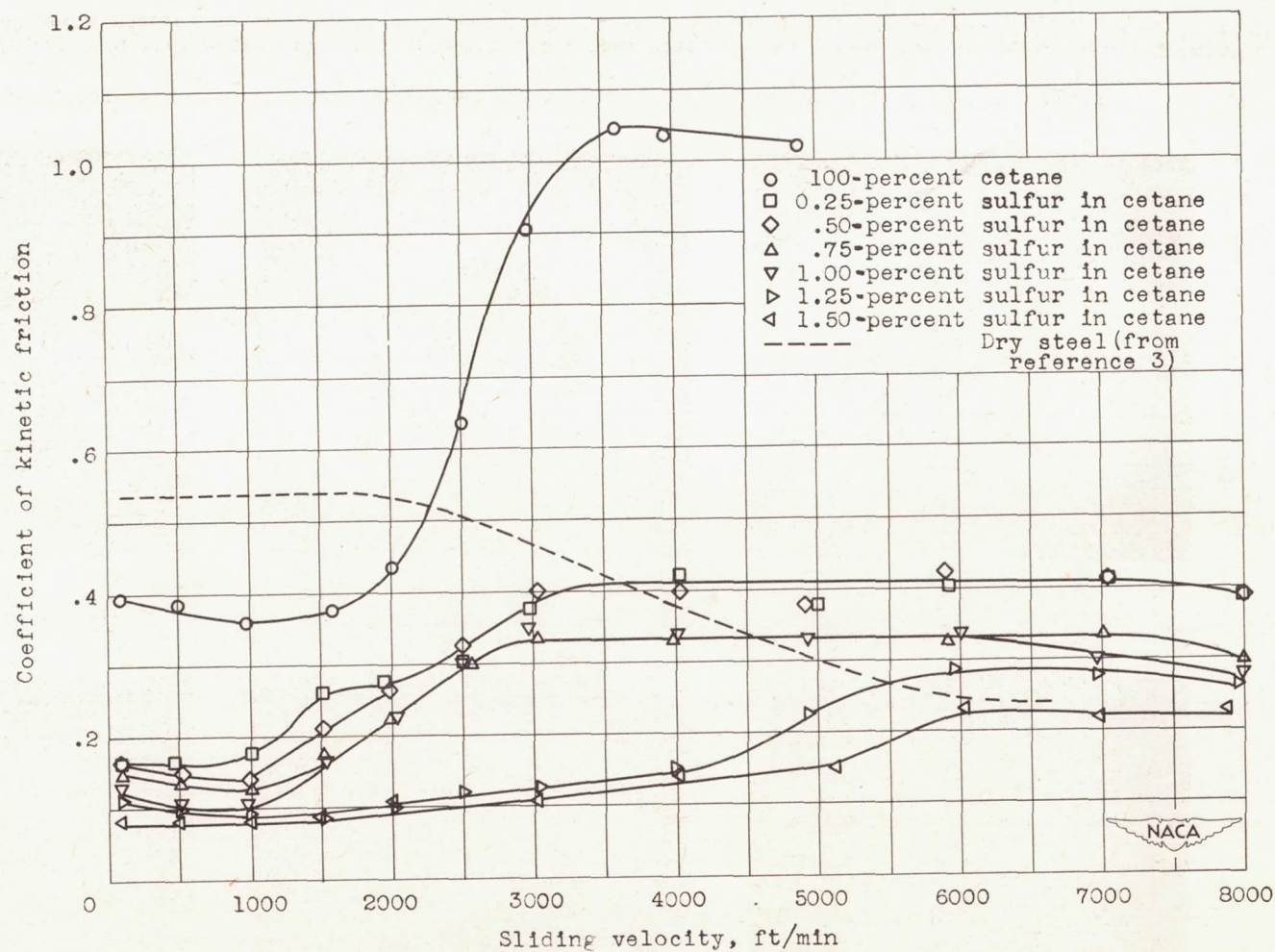


Figure 2. - Effect of sliding velocity on friction for steel surfaces lubricated with pure cetane. Load, 269 grams (126,000 lb/sq in., initial Hertz stress).



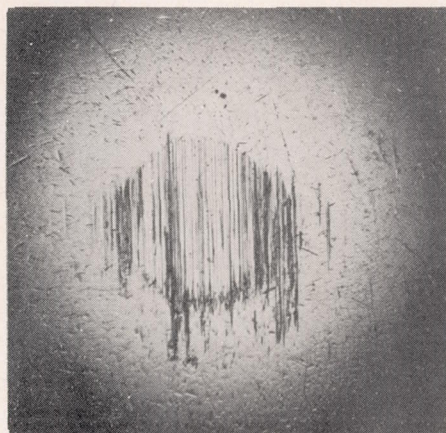
(a) Effect of 0.5-percent free sulfur in cetane.

Figure 3. - Effect of sliding velocity on friction for steel surfaces lubricated with cetane containing free sulfur. Load, 269 grams (126,000 lb/sq in., initial Hertz stress).

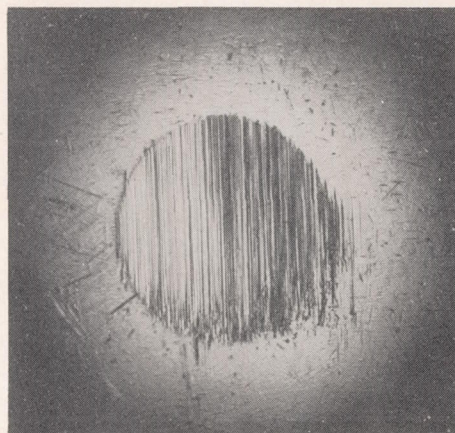


(b) Effect of various concentrations of free sulfur in cetane.

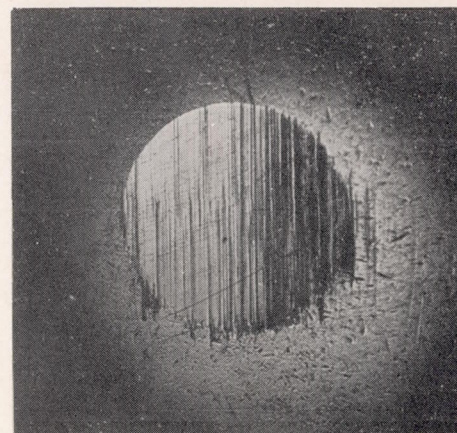
Figure 3. - Concluded. Effect of sliding velocity on friction for steel surfaces lubricated with cetane containing free sulfur. Load, 269 grams (126,000 lb/sq in. initial Hertz stress).



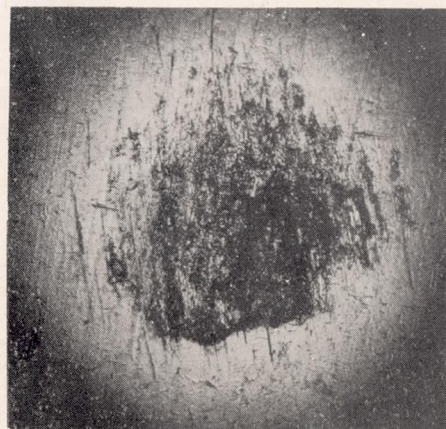
(a) 75 feet per minute.



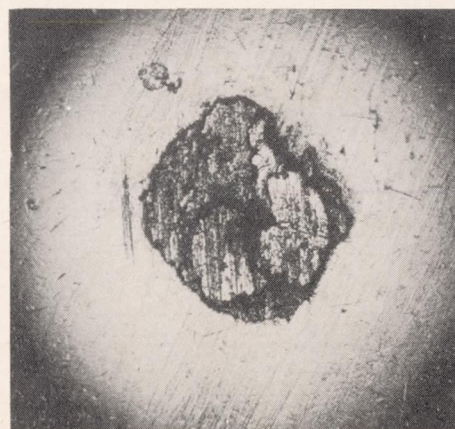
(b) 500 feet per minute.



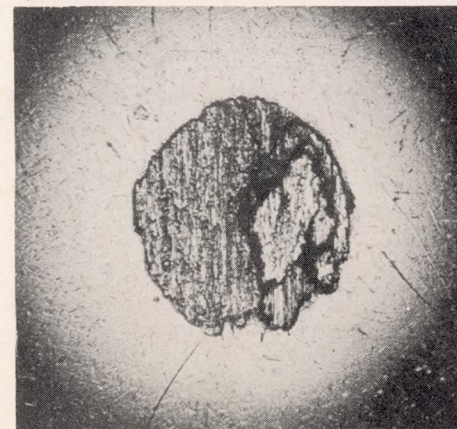
(c) 1000 feet per minute.



(d) 1500 feet per minute



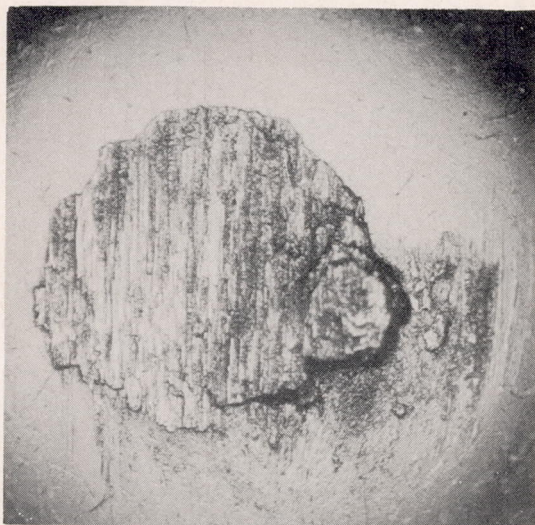
(e) 2500 feet per minute.



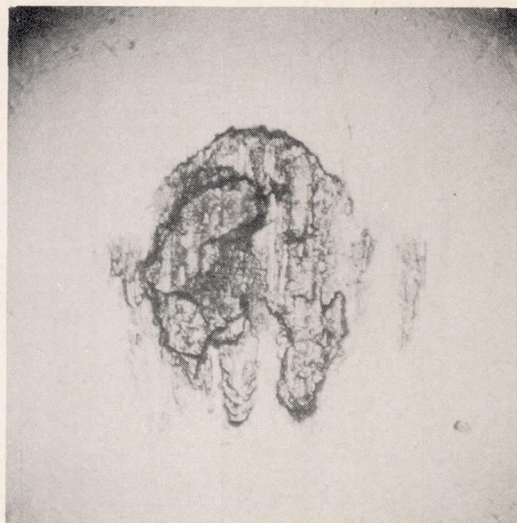
(f) 3000 feet per minute.

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Figure 4. - Photomicrographs of wear areas after friction runs at varied sliding velocities with 269 grams load (126,000 lb/sq in., initial Hertz stress) on SAE 1020 steel lubricated with cetane containing 0.5-percent sulfur. X100



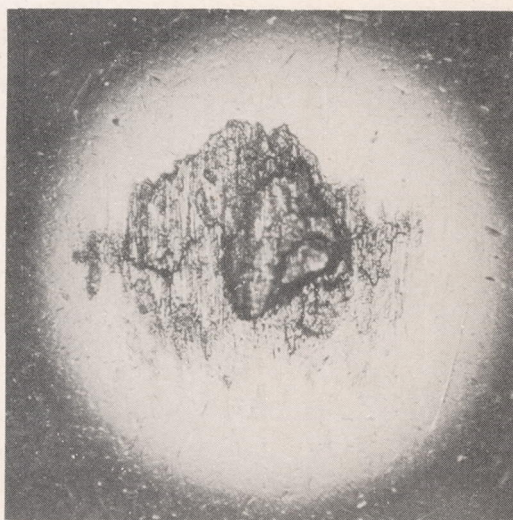
(a) wear spot on spherical rider lubricated with pure cetane. (Mating surface shown in fig. 5(e).)



(b) Wear spot on spherical rider lubricated with cetane plus 0.50-percent sulfur.

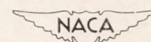


(c) Wear spot on spherical rider lubricated with cetane plus 1.00-percent sulfur. (Mating surface shown in fig. 5(f).)

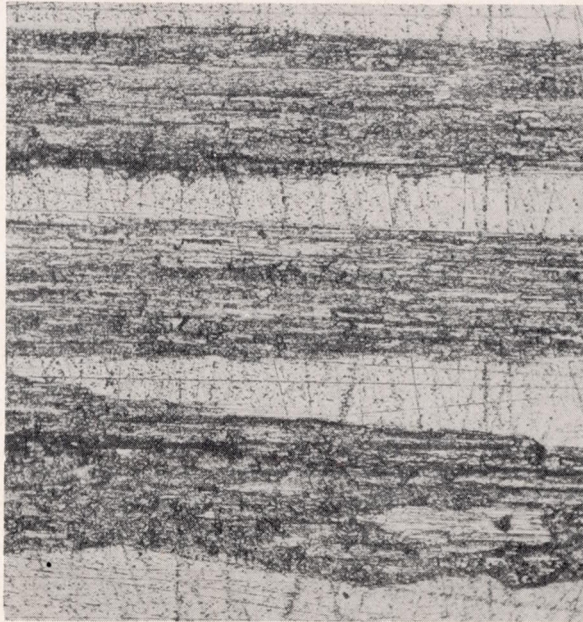


(d) Wear spot on spherical rider lubricated with cetane plus 1.50-percent sulfur.

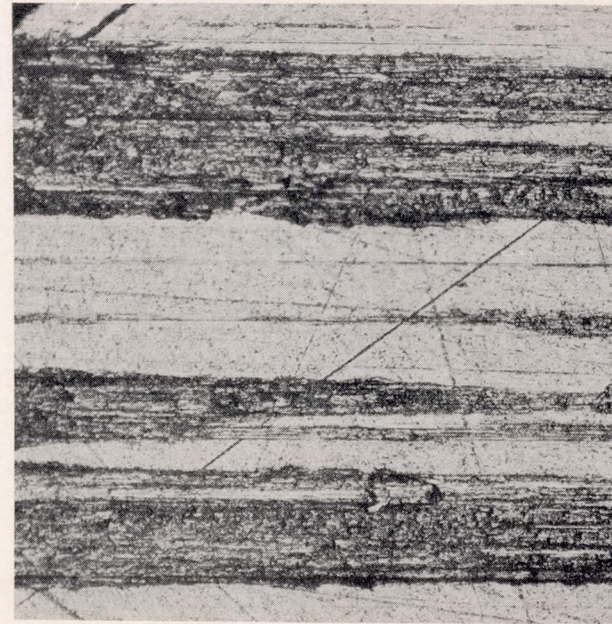
Figure 5. - Photomicrographs of wear areas after wear runs for 6 seconds sliding at 2000 feet per minute with load of 269 grams (126,000 lb/sq in., initial Hertz stress) on SAE 1020 steel lubricated with special lubricants. X100



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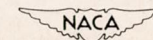


(e) Wear track on disk specimen lubricated with pure cetane. (Mating surface shown in fig. 5(a).)



(f) Wear track on disk specimen lubricated with cetane plus 1.00-percent sulfur. (Mating surface shown in fig. 5(c).)

Figure 5. - Concluded. Photomicrographs of wear areas after wear runs for 6 seconds sliding at 2000 feet per minute with load of 269 grams (126,000 lb/sq in., initial Hertz stress) on SAE 1020 steel lubricated with special lubricants. X100



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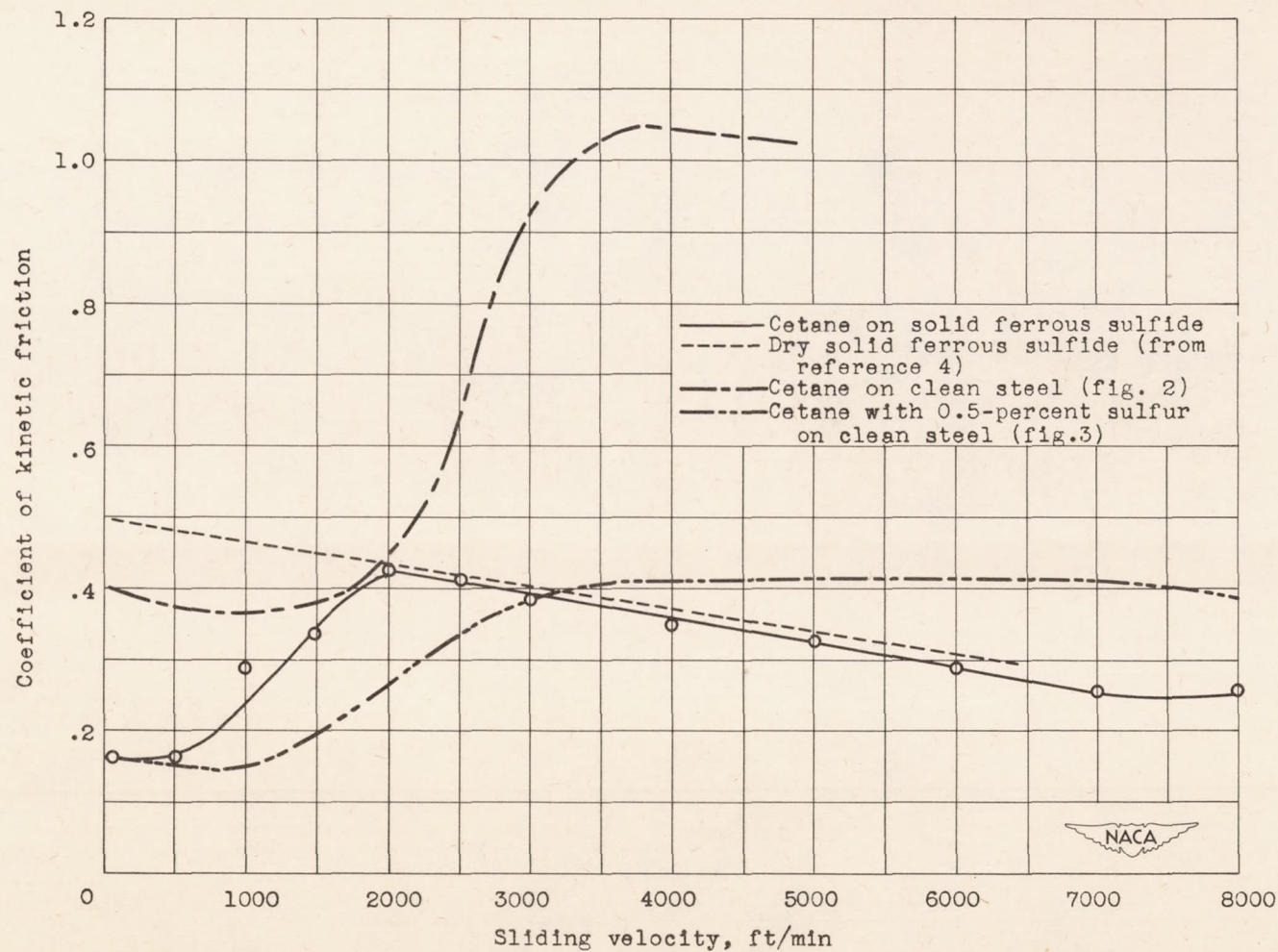
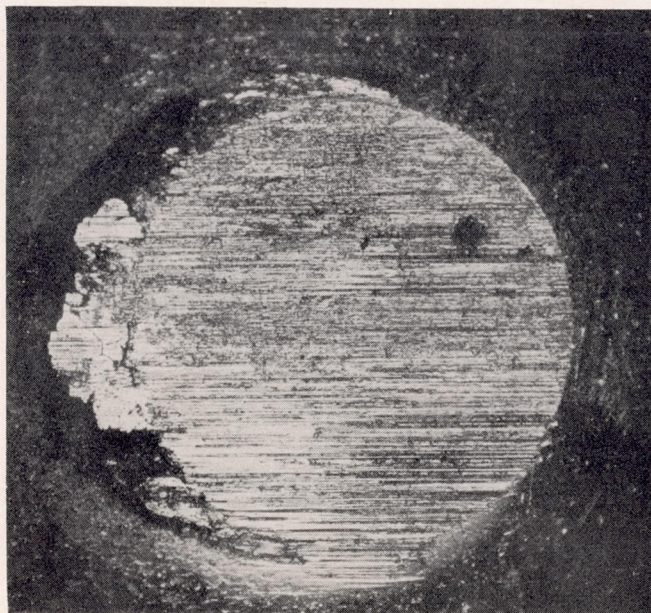
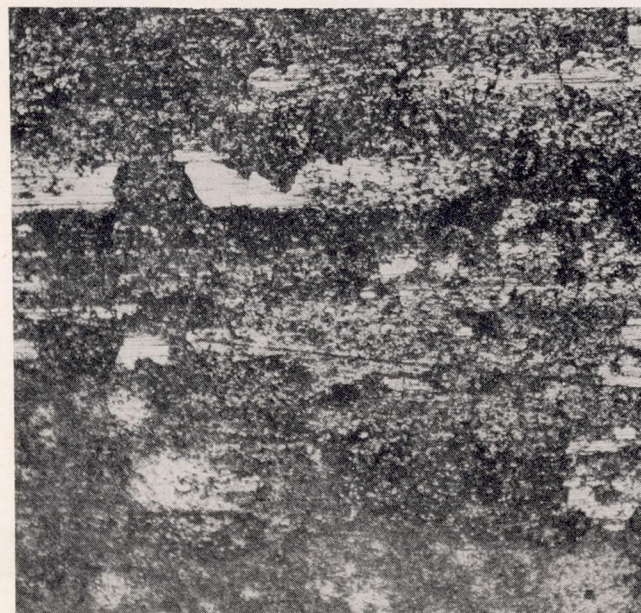


Figure 6. - Effect of sliding velocity on friction for steel disk with solid film of ferrous sulfide lubricated with pure cetane. Load, 269 grams (126,000 lb/sq in., initial Hertz stress).



(a) Wear spot on spherical rider; kinetic friction, 0.42; wear-spot diameter, 0.030 inch. (Mating surface shown in fig. 7(b).)



(b) Wear track on SAE 1020 steel disk specimen with ferrous-sulfide film lubricated with cetane.

Figure 7. - Photomicrographs of wear areas after 6 seconds operation at 2000 feet per minute with load of 269 grams (126,000 lb/sq in., initial Hertz stress). X100

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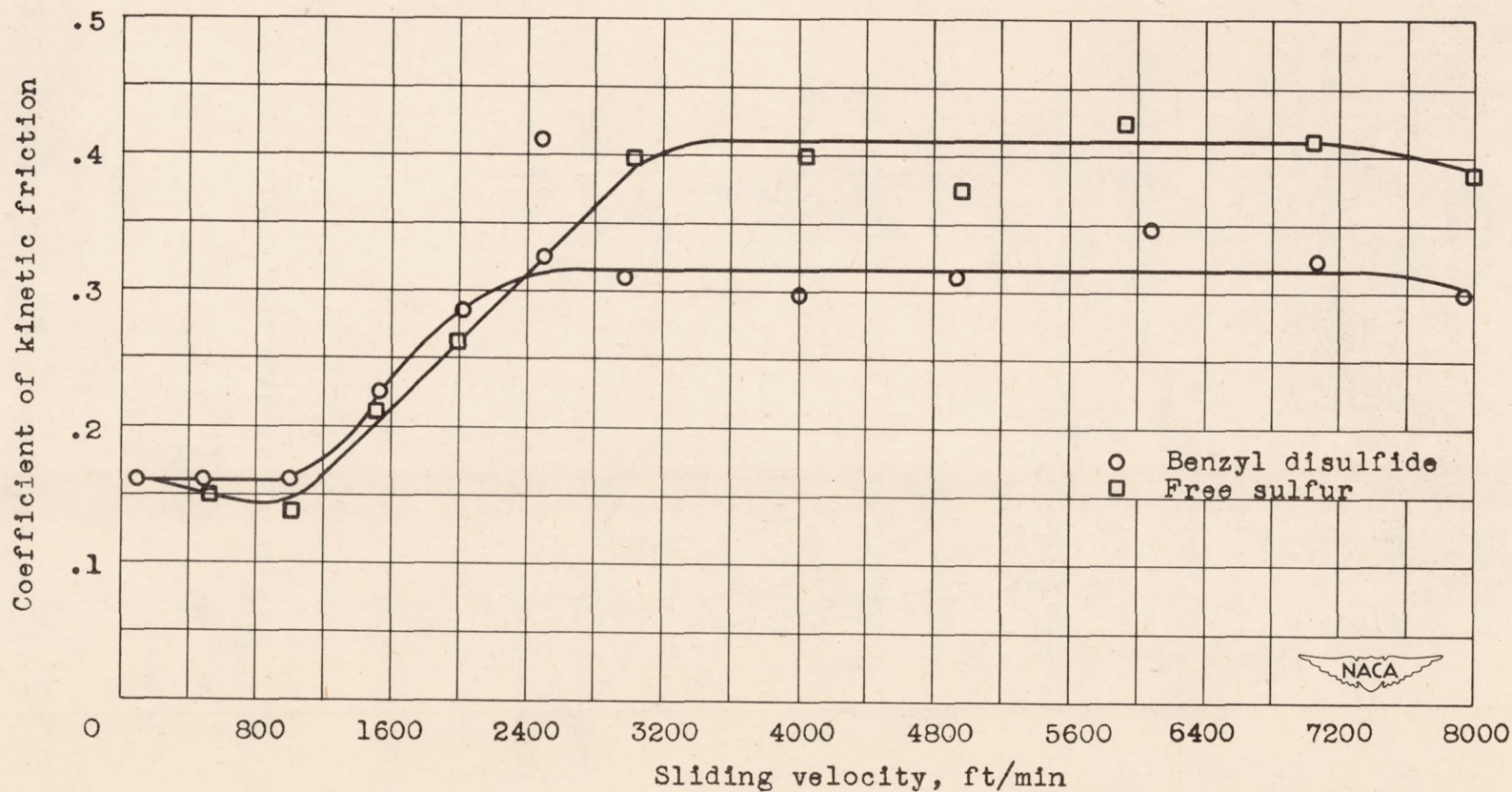


Figure 8. - Effect of sliding velocity on friction, 0.5-percent sulfur from different additives in pure cetane. Load, 269 grams (126,000 lb/sq in., initial Hertz stress).

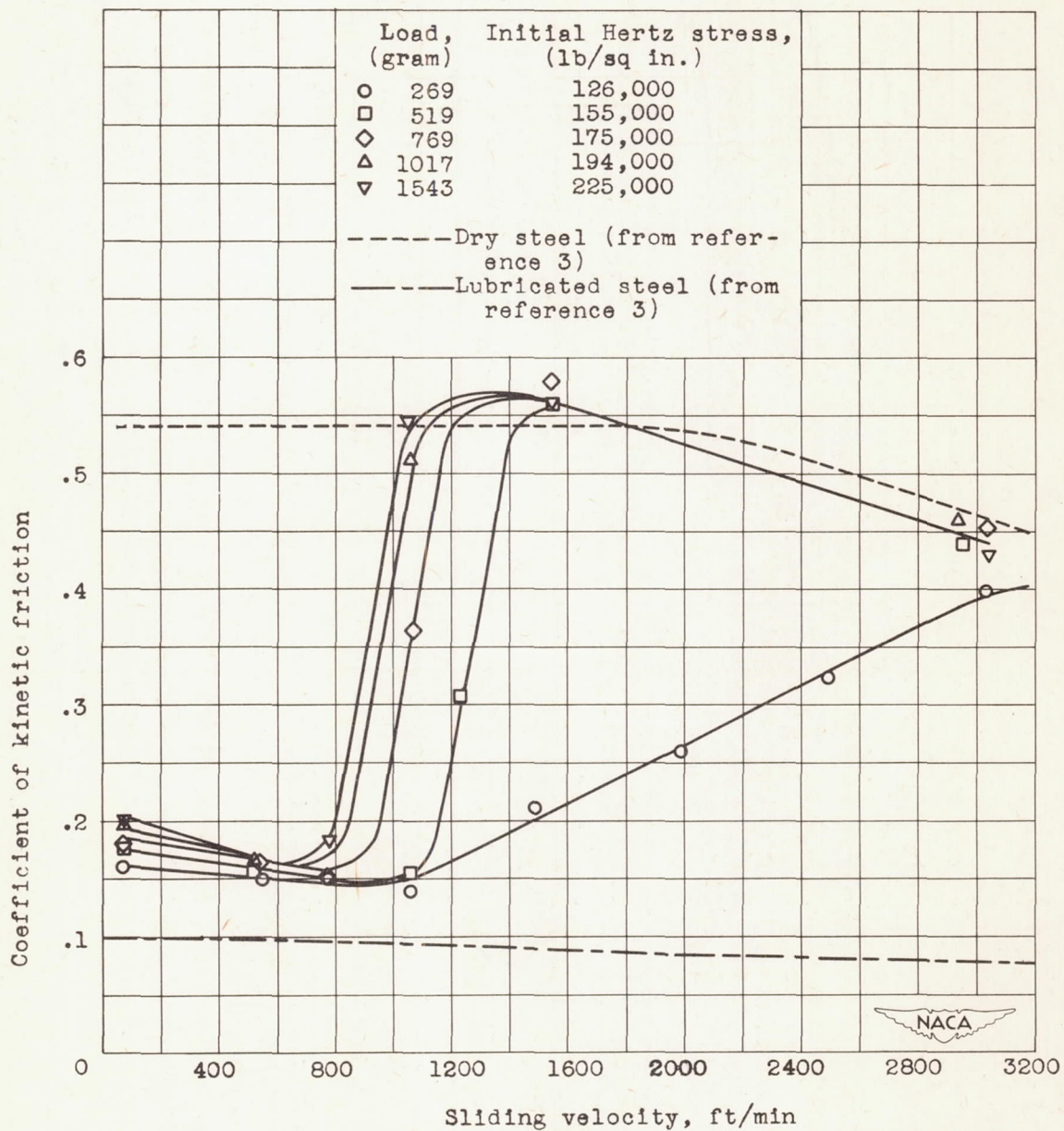


Figure 9. - Effect of sliding velocity on friction with various loads. Steel specimens lubricated with cetane containing 0.5-percent sulfur.